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Monterey, California

THESIS

APPLICATION OF THE LAGGED-AVERAGED TECHNIQUE TO TROPICAL CYCLONE TRACK PREDICTIONS

by

A. Ben Bacon

June 1989

Thesis Advisor Russell L. Elsberry

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The lagged-averaged forecast (LAF) technique applied to tropical cyclone track prediction is a weighted sum of recent orecasts that were started from initial conditions at various times lagging the start of the forecast period. The goal of this ·tudy is to reduce the track forecast error at t + 24 h. Two tests of the LAF approach are presented to demonstrate feasibilty. The first test uses the nine CLIPER forecasts initiated at 24, 30, 36, 42, 48, 54, 60, 66 and 72 h prior to the common verifying ime. In this test, the mean 24-h forecast error is reduced by 8 % relative to the 24-h CLIPER forecast above. In the second est, the "modified" LAF involves only the five CLIPER forecasts initiated at 24, 36, 48, 60 and 72 h prior to the verifying ime. However, the 36-h through 72-h CLIPER forecasts are first modified using statistical regression equations that include predictors related to new track information since these forecasts were initiated. Significant reductions in the track forecast error result from these statistical adjustments. The modified LAF applied to an independent sample results in a reduction rom 189 km to 124 km in the mean 24-h forecast error or a reduction of 34 %. This is a significant improvement because he JTWC mean 24-h forecast error for the last four years is approximately 210 km. The standard deviations are significantly reduced from 118 km to 69 km. Because the combination of the modified CLIPER forecasts in the LAF technique results in a significant improvement in performance, it is recommended that this technique be applied operationally and also be tested with dynamical models.

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Application of the lagged-averaged technique to tropical cyclone track predictions

by

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Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY

from the

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June 1989

ABSTRACT

The lagged-averaged forecast (LAF) technique applied to tropical cyclone track prediction is a weighted sum of recent forecasts that were started from initial conditions at various times lagging the start of the forecast period. The goal of this study is to reduce the track forecast error at t + 24 h. Two tests of the LAF approach are presented to demonstrate feasibilty. The first test uses the nine CLIPER forecasts initiated at 24, 30, 36, 42, 48, 54, 60, 66 and 72 h prior to the common verifying time. In this test, the mean 24-h forecast error is reduced by 8 % relative to the 24-h CLIPER forecast above. In the second test, the "modified" LAF involves only the five CLIPER forecasts initiated at 24, 36, 48, 60 and 72 h prior to the verifying time. However, the 36-h through 72-h CLIPER forecasts are first modified using statistical regression equations that include predictors related to new track information since these forecasts were initiated. Significant reductions in the track forecast error result from these statistical adjustments. The modified LAF applied to an independent sample results in a reduction from 189 km to 124 km in the mean 24-h forecast error or a reduction of 34 %. This is a significant improvement because the JTWC mean 24-h forecast error for the last four years is approximately 210 km. The standard deviations are significantly reduced from 118 km to 69 km. Because the combination of the modified CLIPER forecasts in the LAF technique results in a significant improvement in performance, it is recommended that this technique be applied operationally and also be tested with dynamical models.

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Finally, I would like to dedicate this work to my wife, Connie. She managed to give me encouragement when I needed it most.

I. INTRODUCTION

Forecasters at the Joint Typhoon Warning Center (JTWC) on Guam have a difficult job in forecasting tropical cyclone movement. This job is made even harder by random and systematic errors in the model guidance used in preparing the forecast. Random errors can arise from the lack of adequate data to initialize the model whereas systematic error are caused by some intrinsic deficiency of the model (Peak and Elsberry 1982). Random errors can cause a 'windshield wiper effect' that rotates model forecast tracks alternately to the left and then to the right of the actual path (Elsberry and Dobos 1989). The forecaster then is not certian if a forecast change in track orientation represents an actual turning or a spurious oscillation.

Several attempts have been made to reduce the systematic error in dynamical track prediction models. Renard *et al.* (1973) used a *post-processing* technique to reduce systematic errors in the Hurricane and Typhoon Track (HATRACK) forecasts. Elsberry and Frill (1980) used a series of regression equations to reduce the systematic error in the Fleet Numerical Oceanography Center (FNOC) Tropical Cyclone Model (TCM). Peak and Elsberry (1982) used a backward extrapolation technique that satisfactorily reduced systematic errors in the HATRACK, TCM and the Nested Two-way interactive Tropical Cyclone Model.

The lagged-averaged forecast technique used with global numerical weather prediction models is one method of reducing the forecast error. Reduction of errors in the model guidance can aid the JTWC forecaster in his/her quest to reduce track forecast errors. The removal of just the random error can save lives and millions of dollars by providing a more accurate and timely forecast of tropical storm movement.

The main objective of this study is to use the lagged-averaged forecast technique to reduce random error in the western North Pacific CLImatology and PERsistance (CLIPER) model. A secondary objective is to provide the framework for future work in applying the lagged-averaged technique to a dynamical model, such as the One-way influence Tropical Cyclone Model (OTCM).

II. DESCRIPTION OF THE LAGGED-AVERAGED TECHNIQUE

The lagged-averaged forecast approach was introduced by Lorenz (1977) who statistically combined a series of previous forecasts to reduce errors. Hoffman and Kalnay (1983) proposed that a combination of forecasts verifying at the time of the present forecast might add valuable information to the present forecast. They called this approach the lagged-averaged forecast (LAF) method. Each LAF ensemble member is an ordinary forecast started from initial conditions at a time lagging the start of the forecast period by a different amount. These forecasts are averaged at the common verification time to obtain

$$LAF = a_i F_i \qquad i = 1, N. \tag{1}$$

In (1), a_i is the weighting factor and F_i is the corresponding LAF ensemble member. The LAF method is operationally feasible since the LAF ensemble members are produced during the normal operational cycle (Hoffman and Kalnay 1983). The LAF was tested as an alternate to Monte Carlo forecast (MCF) method. In the simplest form of the MCF method, an ensemble of initial states is selected randomly from a collection of possible initial states. Each ensemble member is then integrated in time and the ensemble of forecasts is used to calculate estimates of the desired statistics. This technique is very expensive because of the number of forecasts that have to be made. Tests by Hoffman and Kalnay showed that the forecast skill of the LAF is slightly superior to the MCF.

Chen (1989) stated that the most difficult task in using the LAF is determining the best weighting factors for each of the past forecasts. For example, incorrect weighting factors may degrade the accuracy of the LAF by weighting a forecast with a larger lag too much relative to a forecast with a smaller lag. The optimal weighting factors should result in a combination of the lagged-averaged forecasts that minimizes random errors.

The lagged-averaged technique applied to tropical cyclone track prediction involves a series of recent forecasts that were started from initial conditions at various times lagging the start of the forecast period (Fig. 1). Consider a 24-h forecast from time t and all available forecasts during the past 48 hours that also are valid at time t + 24 h. During the past 48 h, eight other forecasts were generated that had a track position that also verified at t + 24 h. The lagged-averaged forecast for t + 24 h is the combination of the nine forecasts. The weights to be applied in (1) to each of the nine forecasts will

be generated here through statistical regression methods. Notice also that these forecasts can be validated at one or more past times from information available at time t. For example, the 72-h forecast made 48 h previously can be validated with known positions at t - 36, t -24, t -12 and t = 0 h (Fig. 1). These validations will be used in a modification of the tropical cyclone LAF.

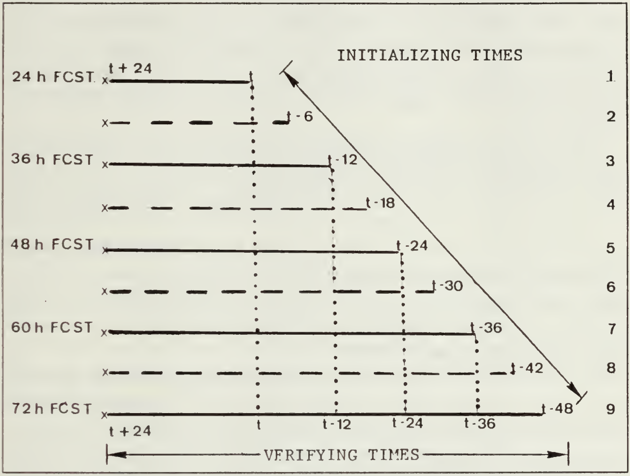

Figure 1. Lagged-averaged forecast diagram showing the nine initializing times as well as the verifying times in relation to the t + 24 h forecast.

III. DATA BASE

A. CLIPER FORECASTS

The CLIPER technique is a prediction scheme based on a series of regression equations using predictors derived from persistence (past 12 h and 24 h storm movement), climatology (time of year and storm location) and storm intensity (maximum sustained surface winds). The 24-h forecasts are based almost entirely on persistence, whereas climatology plays a bigger role at 48 h and almost completely dominates the technique at 72 h.

CLIPER is used in this test of the feasibility of the LAF technique because it is a forecast technique that is available every six hours to the forecasters at JTWC. Consequently, nine CLIPER forecasts can be combined as in Fig. 1. Other techniques such as the dynamical models are available each 6 h, but they are based on new information only each 12 h. Only five such 12-h forecasts are then available for combination in the LAF technique. CLIPER may be considered as a no-skill type of forecast aid. If this lagged-averaged technique can improve CLIPER, then it is expected that the LAF could be applied to dynamically-based forecasts, such as those made by the the One-way influence Tropical Cyclone Model (OTCM).

Dr. T. Tsui and Mr. R. Miller of the Naval Environmental Prediction Research Facility (NEPRF) provided the files of warning positions used to generate the CLIPER forecasts. Mr. P.H. Dobos of the Naval Postgraduate School produced the forecasts using the western North Pacific CLIPER (or WPCLPR) technique developed by Xu and Neumann (1985). The CLIPER forecasts that are used in this study are generated using warning positions for the years 1984 - 87. A total of 109 storms occurred during this period (Table 1).

Table 1. TROPICAL CYCLONES PER YEAR (ATCR 1984, 85, 86 AND 87).

Year	1984	1985	1986	1987
Supertyphoon	2	1	3	6
Typhoon	14	16	16	12
Tropical Storm	11	9	8	6
Tropical Depression	3	1	0	1
Total Tropical Cyclones	30	27	27	25

The CLIPER forecasts are divided into dependent and independent data sets. The dependent set consists of all tropical cyclones that occurred during 1984 - 86. These storms accounted for 1598 CLIPER forecasts. Each forecast contains 12-, 24-, 36-, 48-, 60- and 72-h forecast positions. In addition to the forecast positions, the data set includes the current warning position and the warning positions for the previous 12 and 24 h used to generate the CLIPER forecasts. The independent set contains the same information for all tropical cyclones for 1987, which accounted for a total of 560 forecasts. The CLIPER forecasts in this study are based on warning positions in contrast to CLIPER forecasts used at JTWC, which use Combined Automatic Response to Query (CARQ) positions. The CLIPER generated with warning positions is not as accurate as the CARQ forecasts since the previous warning positions at 12 and 24 h are not updated with new information as is the CARQ.

B. BEST TRACK DATA

Dr. T. Tsui and Mr. R. Miller of NEPRF also provided the files of Best Track (BT) information.The BT positions are based on a post-storm analysis at JTWC that takes into account all of the available data, including aircraft fixes, satellite fixes, surface and aircraft radar fixes and even an occasional ship fix. The BT is a complete history of the storm track that represents only the large-scale motion because the smaller oscillations have been removed.

The BT set includes 2308 positions in the dependent set and 1016 positions in the independent set. The reason for the larger number of positions in the BT set than in the CLIPER set is that a CLIPER forecast can be generated only after the storm has existed 24 h.

C. FORECAST ERRORS

The most widely used measure for verification of a tropical cyclone track is Forecast Error (FE), which is defined as the great circle distance between the forecast position and the best track position. In this feasibility study, FE is computed by taking the 24 h forecast position and subtracting it from the corresponding BT position (Fig. 2). The ΔX and ΔY are squared and added, and the square root of the sum is then the FE. The longitude (ΔX) position is corrected for latitude by multiplying by the cosine of the average latitude between the BT position and the 24-h position. FE are compiled in terms of mean, median and standard deviation as measures of the improvement by the LAF

method. The mean forecast error (MFE) is simply the total of all the FE divided by the number of forecasts.

As discussed by Neumann and Pelissier (1981), FE is not an absolute measure of error, because the best track position contains uncertainties. As indicated above, the BT is a position determined during post-storm analysis at JTWC, and is subjectively smoothed to represent the overall large scale movement of the tropical cyclone (Sheets 1986). Despite this limitation, FE will be used here as the measure of forecast skill.

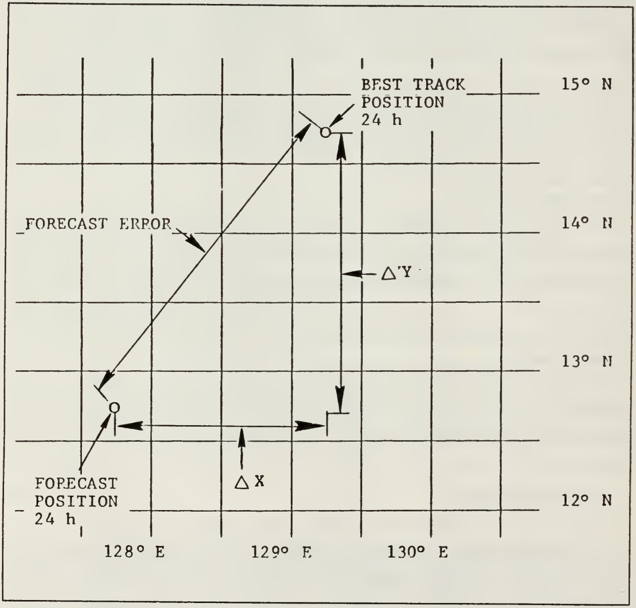

Figure 2. Schematic diagram depicting forecast error.

IV. PROCEDURES AND RESULTS

A. LAGGED-AVERAGED FORECAST APPLICATION

The first test of the lagged-averaged method uses a series of nine CLIPER forecasts verifying at 24 h as in Fig. 1. For example, a 72-h forecast made at 0000 UTC on the 17th will verify at 0000 UTC on the 20th. The 60-h forecast made at 1200 UTC on the 17th will also verify at 0000 UTC on the 20th, along with the 48-h forecast made at 0000 UTC on the 18th, the 36-h forecast made at 1200 UTC on the 18th and the 24-h forecast made at 0000 UTC on the 19th.

In the first step, the CLIPER forecasts are arranged so that for each date-time group (DTG) the entry consists of the 24-, 36-, 48-, 60- and 72-h forecasts all valid at DTG + 24 h. To get the DTG for each forecast to the correct day, a calendar program is used to add one day to the DTG. Linear interpolation between these forecasts is used to calculate 18-, 30-, 42-, 54- and 66-h forecasts. All longitudes computed by linear interpolation are corrected for latitude by using the cosine of the average latitude between the two interpolated points. Thus, the data base contained all nine forecasts valid at one time as in Fig. 1. One restriction with this method is that all the information in the first 54 h of any storm is never used because the statistical regression program uses only the DTG entries with all nine forecasts in the regression technique. For a DTG with all nine forecasts valid at the same time, it is necessary to bypass the first 54 h. This restriction causes short-lived storms to be eliminated from the data set.

Using a linear regression of this data set, equations similar to (1) are produced for predicting the lagged-averaged 24 h latitude (NLAT) and 24 h longitude (NLON). The equation for NLAT is provided all the nine forecast latitudes as predictors, and the predictand is the BT latitude for the verifying DTG. A similar procedure is used for NLON with nine forecast longitudes as predictors, and the predictand is the BT longitude. The resulting regression equations are

$$NLAT = 0.75\,LT24 + 0.33\,LT30 - 0.03\,LT42 - 0.04\,LT54 - 0.019\,LT66 \tag{2}$$

$$NLON = 1.26\,LN30 - 0.25\,LN54 - 0.005\,LN66. \tag{3}$$

In the above equations, LT24, LT30, LT42, LT54, LT66, LN30, LN54 and LN66 are the latitude (LT) and longitude (LN) of the forecasts initiated at the number of hours indi-

cated. These variables are from the complete group of 18 forecast positions (latitudes and longitudes) from 24 to 72 h. The 'MINITAB RELEASE 5.1' regression technique first checks the predictors for correlation with other predictors (Minitab 1985). This correlation is called "multicollinearity." If the correlation is very high (an R-Squared value greater than 99.99%), the predictor is eliminated from the regression equation.

The analysis of variance tables for each regression are given in Table 2 and 3. In the analysis of variance tables, the sequential sums of squares (SEQ SS) are shown. The first line gives SS(X2:X1), i.e., the reduction in the SS residual due to the fitting of the X2 term. The next line gives SS(X3:X1,X2), i.e., the reduction in SS residual due to the fitting of the X3 term, given that X2 has already been added. The next line (if any) is SS(X4:X1,X2,X3) and so on.

Table 2. ANALYSIS OF VARIANCE FOR THE LATITUDE REGRESSION EQUATION.

Source	Degrees of Freedom	Sums of Squares
Regression	5	400399
Error	736	1914
Total	741	402313
Source	Degrees of Freedom	Sequential Sums of Squares
LT24	1	400359
LT30	1	19
LT42	1	16
LT54	1	5
LT66	1	0

Table 3. ANALYSIS OF VARIANCE FOR THE LONGITUDE REGRESSION EQUATION.

Source	Degrees of Freedom	Sums of Squares
Regression	3	12876326
Error	738	4768
Total	741	12881094
Source	Degrees of Freedom	Sequential Sums of Squares
LN30	1	12875511
LN54	1	815
LN66	1	0

The 24-h forecast errors from applying (2) and (3) to the dependent data set are shown in Table 4. This forecast error is calculated by comparing the regression derived NLAT and NLON with the BT positions at the verifying time. Also shown are the 24-h forecast errors of the same data set without application of the regression equations.

Table 4. 24-H FORECAST ERROR USING THE LAF TECHNIQUE WITH THE DEPENDENT DATA.

Unmodified 24-h Forecast Error (km)	Mean	Median	Standard Deviation
	254	214	183
LAF 24-h Forecast Error (km)	Mean	Median	Standard Deviation
	233	193	172

The regression equation applied to the dependent data set decreased the mean 24-h forecast error by 8 % and the standard deviation of the 24-h forecast error by 6 %. Since the decrease was small, the independent data set was not run and this method was modified, as described in the next section.

B. MODIFIED LAGGED-AVERAGED APPROACH

The second approach is a modification of the nine lagged-averaged forecast technique in Fig. 1. Only the five CLIPER forecasts at 24, 36, 48, 60 and 72 h are used because the interpolated positions at the intermediate times did not appear to add

significant new information. The calendar program is used to add 1 day to the 24 h DTG, 1.5 days to the 36 h DTG and so on until 3 days are added to the 72 h DTG. Using the calendar program in this method eliminated the undesirable feature of eliminating the first 54 h of every storm as in the first test.

1. Modified CLIPER Forecasts

In this second test, the 36-, 48-, 60- and 72-h CLIPER forecasts will be first modified to take into account additional information about the actual storm positions from that time until the time the 24-h CLIPER forecast is initiated (Fig. 1). For example, the 12-h position in the 36-h CLIPER forecast can now be verified from the warning position from which the 24-h CLIPER forecast is initiated. In principle, this present information can be used to modify the 36-h CLIPER forecast prior to its use in the LAF. To derive the desired modifications, the difference between the 36-h CLIPER forecast position and the verifying BT position after 36 h is used as the predictand. In this data set, ΔY corresponds to the latitudinal displacement and ΔX corresponds to the longitudinal displacement. The ΔX difference is corrected for latitude by multiplication by the cosine of the average between the BT latitude and the 36-h forecast latitude (Fig. 3).

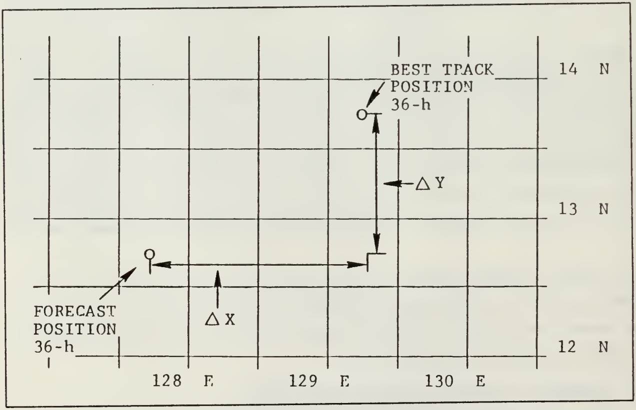

Figure 3. Schematic diagram of the longitudinal and the latitudinal error, ΔX and ΔY, of the 36-h CLIPER forecasts relative to the BT positions.

In addition to the new knowledge about actual storm positions early in each CLIPER forecast, other predictors such as past positions, past displacements, CLIPER displacements and deviations of the CLIPER forecast positions are used in the statistical modification (Fig. 4). These predictors are similar to those used by Peak and Elsberry (1982) in a post-processing technique for adjusting tropical cyclone tracks.

The past-position predictors defined in Table 5 include the previous positions of the storm that are available at the time of the forecast, which establish a general track orientation and speed. For example, the 12 and 24 h past positions are available for a 36-h CLIPER forecast made 12 h previously. Thus, the t = 0 h (current position), t - 12 h, t - 24 h and t - 36 h are available as possible predictors to modify the 36-h CLIPER forecast in Fig. 4.

The past-displacement predictors in Table 5 are computed using the current storm position (time t) and subtracting the previous positions at 12, 24 and 36 h in the case of a 36-h CLIPER forecast made 12 h ago. The zonal and meridional differences for these prior times will generate six predictors.

The CLIPER-displacement predictors in Table 4 are computed relative to the warning position at the time of the forecast, which is t - 12 h in the case of the 36-h forecast in Fig. 4. This initial position is subtracted from the 12-h forecast position, the 24-h forecast position and the 36-h forecast position. These zonal and meridional differences lead to six more predictors.

As indicated above, the deviations of early portions of the CLIPER forecasts from the known warning positions prior to the current time are expected to be key predictors. In the case of a 36-h forecast made 12 h ago, the 12-h CLIPER forecast position (valid at time t) is subtracted from the current position at time t. These zonal and meridional differences generate two additional predictors.

A total of 22 predictors are available for the latitude and longitude regression equations for modifying the 36-h CLIPER forecast (Fig. 4 and Table 5). Data sets for modifying the CLIPER forecasts at 48, 60 and 72 h are generated in a similar fashion using the forecast data sets along with the BT set. If the DTG of each set matched, the BT position was subtracted from the corresponding forecast position to calculate the predictands. The predictors for the 48-, 60- and 72-h regression equations are calculated in a similar fashion. A total of 30 predictors are available for the 48 h (Fig. 5), 38 predictors for the 60 h (Fig. 6) and 46 predictors for the 72 h (Fig. 7) regression equations.

More predictors are available for the longer forecast because two more predictors of each type occur. Then the forecast error was calculated using each computed ΔX and ΔY (see chapter on error statistics for description of forecast error). The data were then run through a statistical program to generate the mean forecast error and the standard deviation. These means and standard deviations will be used to illustrate the improvements in the modified CLIPER forecasts at 36, 48, 60 and 72 h.

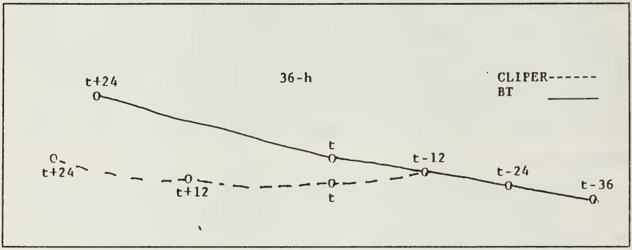

Figure 4. Schematic diagram of the 36-h predictors relating the CLIPER forecasts, past positions and BT positions for modification of the 36-h CLIPER forecast.

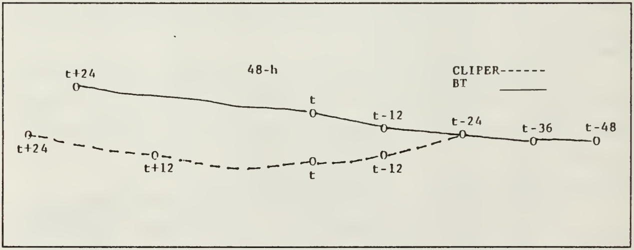

Figure 5. Schematic diagram of the 48-h predictors as in Figure 3, except for the modification of the 48-h CLIPER forecast.

Table 5. PREDICTORS AVAILABLE FOR THE REGRESSION EQUATIONS MODIFYING THE 36-H CLIPER FORECASTS.

Predictor Type Predictor Name	Reference Postion	Number of each type of predictor
Past-Position (deg)		8
PP36A	LT(t)	
PP36B	LN(t))	
PP36C	LT(t - 12)	
PP36D	LN(t - 12)	
PP36E	LT(t - 24)	
PP36F	LN(t - 24)	
PP36G	LT(t - 36)	
PP36H	LN(t - 36)	
Past-Displacement (km)		6
PD36A	LT(t) - LT(t - 12)	
PD36B	LN(t) - LN(t - 12)	
PD36C	LT(t) - LT(t - 24)	
PD36D	LN(t) - LN(t - 24)	
PD36E	LT(t) - LT(t - 36)	
PD36F	LN(t) - LN(t - 36)	
CLIPER-Displacement (km)		6
CD36A	LT CLP(t) - LT(t - 12)	
CD36B	LN CLP(t) - LN(t - 12)	
CD36C	LT CLP(t + 12) - LT(t - 12)	
CD36D	LN CLP(t + 12) - LN(t - 12)	
CD36E	LT CLP(t + 24) - LT(t - 12)	
CD36F	LN CLP(t + 24) - LN(t - 12)	
Deviation of CLIPER forecast from Warning position (km)		2
DEV36A	LT CLP(t) - LT(t)	
DEV36B	LN CLP(t) - LN(t)	
Total Predictors for 36 h regression equation		22

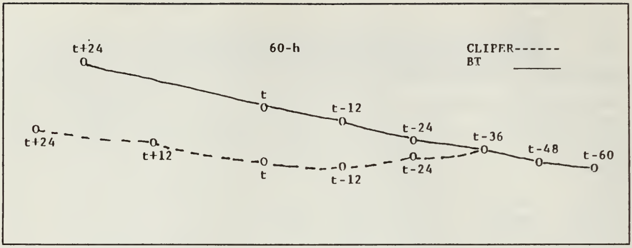

Figure 6. Schematic diagram of the 60-h predictors as in Figure 3, except for the modification of the 60-h CLIPER forecast.

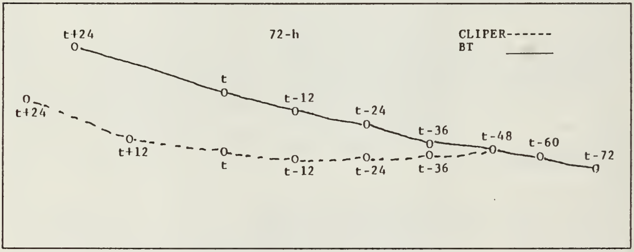

Figure 7. Schematic diagram of the 72-h predictors as in Figure 3, except for the modification of the 72-h CLIPER forecast.

Regression equations for modifying the 36-, 48-, 60- and 72-h CLIPER forecasts are generated using a standard stepwise regression technique from 'MINITAB VERSION 5.1'. All of the predictors (latitudinal and longitudinal) are entered in the regressions for the latitudinal (ΔY) and for the longitudinal (ΔX) modifications. The predictors are entered (forward stepped) one at a time based on a T-ratio value greater than 2.0. As a predictor is added to the equation, the T-ratios for that predictor, as well as all of the predictors in the equation at that time, are computed. This allows for the

removal during each step of a predictor that drops below the 2.0 T-ratio criterion. In addition to the T-ratio criterion, the amount of variance (R-squared) accounted for by the addition of each predictor must have contributed at least a one percent increase.

Once the regression equations are produced, each DTG of data run through the regression equations will produce a new ΔX and ΔY . Then in the case of the 36-h CLIPER forecast, the new ΔX and ΔY are first converted to degrees and added to their respective longitudinal and latitudinal 36-h CLIPER forecast positions. This procedure is applied to the 48-, 60- and 72-h CLIPER forecasts to arrive at the modified forecast position data sets. This was done with the dependent and independent data sets.

Using the above criteria, the regression equations for modifying the latitudinal and longitudinal positions of the 36-h CLIPER forecast are

$$MOD36LT = -1.18\,PD36C + 4.54\,PP36B + 0.4\,CD36C + 4.88\,PP36E - 509.2 \tag{4}$$

$$MOD36LN = -1.61\,PD36D + 0.46\,CD36F - 0.29\,CD36E + 0.4\,PD36F + 7.1\,PP36E - 121.03. \tag{5}$$

The predictors (see Table 5) in the regression equations are listed in the order in which they entered the equation. In all the regression equations modifying the CLIPER forecasts, the past-displacement (PDtt) predictors are selected as the primary predictors. The predictor chosen least often was the deviation of early portions of the CLIPER from the known warning positions prior to the current time. The Analysis of Variance (AOV) in Table 6 contains the T-ratio and the amount of the variance that is explained by the addition of each predictor to the regression equation. The percent of the variance accounted for by the latitude regression equation is larger than for the longitude regression equation even though the longitude equation contains more predictors. The latitude equation accounts for more variance than the longitude equation in all of the equation sets. This is probably because the latitude errors are smaller than the longitude errors.

Table 6. ANALYSIS OF VARIANCE FOR 36-H REGRESSION EQUATIONS FOR MODIFIED LATITUDE AND LONGITUDE.

36 h Predictors (LT)	T-Ratio	Percent of variance accounted for by each predictor
PD36C	-24.65	52.16
PP36B	12.49	9.98
CD36C	6.96	2.04
PP36E	5.62	1.03
Percent of variance accounted for by the regression equation		65.21
36 h Predictors (LN)	T-Ratio	Percent of variance accounted for by each predictor
PD36D	15.14	40.47
CD36F	15.27	7.64
CD36E	-9.37	4.01
PD36F	5.54	1.62
PP36E	5.12	1.1
Percent of variance accounted for by the regression equation		54.84

Table 7 shows the results of the adjustments to the 36-h CLIPER latitude (MOD36LT) in (4) and longitude (MOD36LN) in (5) being added to the 36-h CLIPER positions for the dependent and independent data sets. These modified positions verify at the same time as the unmodified 24-h CLIPER positions. The forecast error statistics are then calculated comparing the unmodified with the modified 36-h CLIPER. The mean forecast error and the standard deviation of forecast error both displayed a significant reduction (Table 7). The dependent data set had a 32 % reduction and the independent data set had a 23 % reduction in the mean forecast error, along with 31 % and 20 % reductions of the standard deviations of the forecast errors.

Table 7. LONGITUDINAL (ΔX), LATITUDINAL (ΔY) AND TOTAL FORECAST ERRORS (KM) FOR 36-H UNMODIFIED AND MODIFIED.

36 h Dependent	ΔX	ΔY	Forecast error	Modified ΔX	Modified ΔY	Modified Forecast Error
Mean	-20	34	367	-45	52	248
Median	-9	33	301	-65	45	216
Standard Deviation	347	265	240	242	162	166
Reduction in mean Forecast Error				119		
Reduction in standard deviation of Forecast Error.				74		
36 h Independent	ΔX	ΔY	Forecast Error	Modified ΔX	Modified ΔY	Modified Forecast Error
Mean	-14	60	311	-81	66	239
Median	-32	56	280	-93	61	213
Standard Deviation	279	243	207	226	149	164
Reduction in mean Forecast Error				72		
Reduction in standard deviation of Forecast Error.				43		

The equations for the modification of the 48-h CLIPER forecasts are

$$MOD48LT = 0.125\,PD48C + 5.35\,PP48B - 1.19\,PD48E + 0.34\,CD48G - 479.9 \quad (6)$$

$$MOD48LN = 0.09\,PD48D + 0.54\,CD48H - 0.42\,CD48G - 1.13\,PD48F$$

$$+ 0.47\,PP36E - 54.3. \quad (7)$$

The AOV (Table 8) shows the T-ratio for the first predictor picked in both the latitude and longitude equations to be below the 2.0 criterion. These T-ratios were greatly reduced by the addition of the last predictor in the table in each case, but the amount of explained variance was so large for each that they were kept in the regression equations. The overall percent of explained variance is larger than for the 36-h equations and again the explained variance was greater for the latitude than for the longitude.

Table 8. ANALYSIS OF VARIANCE FOR 48-H REGRESSION EQUATIONS FOR MODIFIED LATITUDE AND LONGITUDE.

48 h Predictors (LT)	T-Ratio	Percent of variance accounted for by each predictor
PD48C	0.88	62.19
PP48B	10.4	8.49
PD48E	-9.33	1.02
CD48G	7.2	1.49
Percent of variance accounted for by the regression equation		73.19
48 h Predictors (LN)	T-Ratio	Percent of variance accounted for by each predictor
PD48D	0.66	46.38
CD48H	19.67	8.32
CD48G	-10.89	4.03
PD48F	-10.69	4.52
Percent of variance accounted for by the regression equation		63.25

Table 9 displays the results of applying MOD48LT in (6) and MOD48LN in (7) to the 48-h CLIPER independent and dependent data sets. After adding the adjustment to the 48-h positions, the mean forecast error is reduced by 45 % for the dependent data and 36 % for the independent sample. The standard deviation of the forecast error is also reduced substantially with reductions of 38 % for the dependent data and 29 % for the independent sample. The errors for 48-h modified CLIPER, which verifies at t + 24 h in Fig. 1, are larger than the modified 36-h CLIPER, that also verifies at t + 24 h.

Table 9. **LONGITUDINAL (ΔX), LATITUDINAL (ΔY) AND TOTAL FORECAST ERRORS (KM) FOR 48-H UNMODIFIED AND MODIFIED CLIPER.**

48 h Dependent	ΔX	ΔY	Forecast Error	Modified ΔX	Modified ΔY	Modified Forecast Error
Mean	-20	59	512	-17	0	288
Median	20	67	436	-40	-3	254
Standard Deviation	494	351	329	301	181	203
Reduction in mean Forecast Error				224		
Reduction in standard deviation of Forecast Error				126		
48 h Independent	ΔX	ΔY	Forecast Error	Modified ΔX	Modified ΔY	Modified Forecast Error
Mean	-12	95	432	-50	19	277
Median	-36	89	386	-62	10	220
Standard Deviation	402	325	298	298	173	212
Reduction in mean Forecast Error				155		
Reduction in standard deviation of Forecast Error				86		

The regression equations for the modification of the 60-h CLIPER forecasts are

$$MOD60LT = 0.47\,PD60E + 5.11\,PP60D - 1.51\,PD60G - 6.97\,CD60K - 418.1 \quad (8)$$

$$MOD60LN = -1.05\,PD60F + 0.38\,CD60L - 0.53\,CD60K - 6.97\,CD60B$$

$$+ 16.0\,PP60M + 3.4\,CD60D - 121.03. \quad (9)$$

In Table 10, the percent of explained variance again is greater for the latitude than for the longitude equation. In the latitude portion of the analysis of variance, the addition of the final predictor to the regression equation, CD60K, causes the percent of variance accounted for by the next to last predictor, PD60G, to fall below one. The predictor, PD60G, was kept in the equation since it still exhibited a large T-ratio.

Table 10. ANALYSIS OF VARIANCE FOR 60-H REGRESSION EQUATIONS FOR MODIFIED LATITUDE AND LONGITUDE.

60 h Predictors (LT)	T-Ratio	Percent of variance accounted for by each predictor
PD60E	2.87	69.19
PP60D	7.85	6.96
PD60G	-9.73	.53
CD60K	8.85	2.09
Percent of variance accounted for by the regression equation		78.77
60 h Predictors (LN)	T-Ratio	Percent of variance accounted for by each predictor
PD60F	-25.61	45.93
CD60L	6.034	12.23
CD60K	-10.27	3.54
CD60B	-6.66	1.8
PP60M	5.71	1.12
CD60D	5.41	1.26
Percent of variance accounted for by the regression equation		65.88

Table 11 shows the results of the adjustments to the 60-h CLIPER latitude (MOD60LT) in (8) and longitude (MOD60LN) in (9) for the dependent and independent samples. These modified 60-h forecasts , as did the unmodified counterparts, verify at the same time as the unmodified 24-h CLIPER positions. The mean forecast error and the standard deviation of forecast error both displayed a significant reduction. The dependent data set had a 50 % reduction and the independent data set had a 34 % reduction in the mean forecast error along with 43 % and 26 % reductions of the standard deviation of the forecast error.

Table 11. **LONGITUDINAL (ΔX), LATITUDINAL (ΔY) AND TOTAL FORECAST ERRORS (KM) FOR 60-H UNMODIFIED AND MODIFIED CLIPER.**

60 h Dependent	ΔX	ΔY	Forecast Error	Modified ΔX	Modified ΔY	Modified Forecast Error.
Mean	4	90	669	-6	0	333
Median	35	100	578	-51	-2	269
Standard Deviation	675	430	448	399	198	296
Reduction in mean Forecast Error				336		
Reduction in standard deviation of Forecast Error				152		
60 h Independent	ΔX	ΔY	Forecast Error	Modified ΔX	Modified ΔY	Modified Forecast Error
Mean	-9	120	563	-42	14	320
Median	-49	144	501	-70	22	250
Standard Deviation	574	390	422	407	183	314
Reduction in mean Forecast Error				243		
Reduction in standard deviation of Forecast Error.				108		

The regression equations for the modification of the 72-h CLIPER forecasts are

$$MOD72LT = 0.82\,PD72G + 5.1\,PP72F - 1.82\,PD72L + 0.55\,CD72M - 397.8 \quad (10)$$

$$MOD72LN = 1.85\,DEV72H - 6.24\,CD72B - 0.8\,CD72G + 0.83\,PD72N + 182.36. \quad (11)$$

The regression equation for the 72-h longitude is the only one in which the modification of the CLIPER forecast included a Deviation from CLIPER as a predictor. It is even picked as the primary predictor. Similar to the 60-h latitude regression equation, the 72-h latitude regression equation has a predictor with the amount of variance accounted for by the predictor, PD72L, of less than one. This predictor is again kept in the equation since its T-ratio is greater than two. As with all the other regression equations, the latitude equation accounts for more variance than the longitude equation.

Table 12. ANALYSIS OF VARIANCE FOR 72-H REGRESSION EQUATIONS FOR MODIFIED LATITUDE AND LONGITUDE.

72 h Predictors (LT)	T-Ratio	Percent of variance accounted for by each predictor
PD72G	4.95	73.43
PP72F	7.0	6.25
PD72L	-11.58	.61
CD72M	11.04	2.99
Percent of variance accounted for by the regression equation		83.28
72 h Predictors (LN)	T-Ratio	Percent of variance accounted for by each predictor
DEV72H	17.29	50.32
CD72B	-10.74	11.62
CD72G	-10.74	3.68
PD72N	7.85	2.85
Percent of variance accounted for by the regression equation		68.47

Table 13 displays the results of applying MOD72LT in (10) and MOD72LN in (11) to the 72-h CLIPER independent and dependent samples. After applying the adjustment to the 72-h CLIPER positions, the mean forecast error is reduced by 52 % for the dependent data and 32 % for the independent sample. The standard deviation of the forecast error is also reduced substantially with reductions of 49 % for the dependent data and 26 % for the independent sample. The errors for 72-h modified CLIPER are the largest of all the modified data sets, which all apply at t + 24 h in Fig. 1.

Table 13. LONGITUDINAL (ΔX), LATITUDINAL (ΔY) AND TOTAL FORECAST ERRORS (KM) FOR 72-H UNMODIFIED AND MODIFIED CLIPER.

72 h Dependent	ΔX	ΔY	Forecast Error	Modified ΔX	Modified ΔY	Modified Forecast Error
Mean	38	131	821	-7	2	369
Median	90	172	719	-33	5	289
Standard Deviation	827	497	524	471	203	356
Reduction in mean Forecast Error				452		
Reduction in standard deviation of Forecast Error				168		
72 h Independent	ΔX	ΔY	Forecast Error	Modified ΔX	Modified ΔY	Modified Forecast Error
Mean	7	149	672	-39	14	343
Median	-60	178	585	-53	23	254
Standard Deviation	706	425	498	467	182	367
Reduction in mean Forecast Error				329		
Reduction in standard deviation of Forecast Error				131		

2. Modified LAF Forecast

These modified CLIPER forecasts are combined with the unmodified 24 h CLIPER forecasts to produce the "modified" lagged-averaged forecast (LAF) equations. Stepwise regression is used with BT positions as the predictands and the modified CLIPER forecasts along with the unmodified 24-h forecasts as the predictors. The resulting equations are

$$N24LT = 0.3\,MOD36LT + 0.2\,MOD60LT + 0.21\,LT24 + 0.16\,MOD72LT + 0.15\,MOD48LT + 0.202. \quad (12)$$

$$N24LN = 0.42\,LN24 + 0.32\,MOD36LN + 0.01\,MOD60LN + 0.07\,MOD72LN + 0.11\,MOD48LN - 1.47. \quad (13)$$

Equations (12) and (13) compare to equations (2) and (3) in that they are based on a lagged-averaged forecast technique, although (2) and (3) have nine available predictors and (12) and (13) draw on only five predictors. The latitude equation (11) uses MOD36LT as the number one predictor. This is something of a surprise since the LT24 was expected to have a greater effect in the regression equation and it was picked only as the third predictor. In the longitude equation (13), LN24 was picked as the number one predictor as expected.

In Table 14, the analysis of variance for equations (12) and (13) is shown. The percent of variance accounted for by each of the additional predictors is less than one, but since the T-ratios are greater than two, the predictors are kept in the equations.

Table 14. ANALYSIS OF VARIANCE FOR 24-H REGRESSION EQUATIONS FOR MODIFIED LAF LATITUDE AND LONGITUDE.

24 h Predictors (LT)	T-Ratio	Percent of variance accounted for by each predictor
MOD36LT	14.94	96.62
MOD60LT	8.61	.26
LT24	10.68	.51
MOD72LT	9.56	.22
MOD48LT	7.92	.13
Percent of variance accounted for by the regression equation		98.74
24 h Predictors (LN)	T-Ratio	Percent of variance accounted for by each predictor
LN24	15.36	98.09
MOD36LN	11.85	.65
MOD60LN	4.57	.12
MOD72LN	4.97	.04
MOD48LN	4.35	.03
Percent of variance accounted for by the regression equation		98.93

Table 15 contains the results of applying (12) and (13) to the dependent and independent data. This resulted in a reduction of mean 24-h forecast error of 35 % for the dependent data and 34 % for the independent sample. This is a significant reduction compared to the 8 % improvement from the first LAF, which was for the dependent

data. The reductions of standard deviation of forecast error are 34 % for the dependent data and 42 % for the independent data, which may be compared to 6 % reduction for the original LAF. Thus, the modifications of the CLIPER forecasts used in the LAF technique result in a significant improvement in preformance.

Table 15. 24 H FORECAST ERROR USING THE MODIFIED LAF FORECAST TECHNIQUE.

Unmodified 24 h Forecast Error	Mean	Median	Standard Deviation
Dependent	223	188	152
Independent	189	166	118
Modified LAF 24 h Forecast Error	Mean	Median	Standard Deviation
Dependent	146	123	103
Independent	124	116	69
Reductions, Dependent sample	77	65	49
Reductions, Independent sample	65	50	49

Figures 8 and 9 display graphically the results of Table 15 for the dependent sample and the independent sample respectively. The solid line in each graph is the unmodified 24, 36, 48, 60 and 72-h mean CLIPER forecast errors. The dotted line represents the modified 36, 48, 60 and 72-h mean forecast errors. These two lines intersect since the 24-h mean forecast errors are not modified. A significant reduction in the mean 24-h forecast errors by the application of the modified LAF is indicated in both samples.

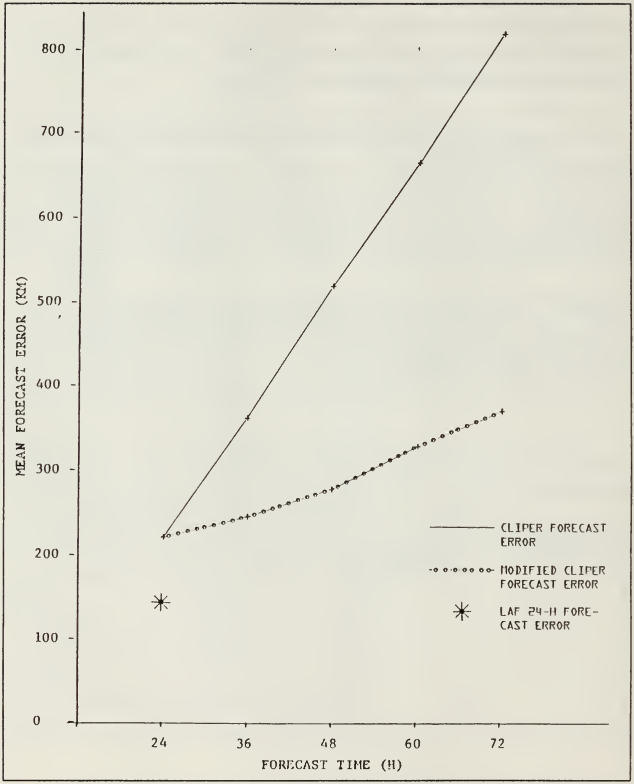

Figure 8. LAF 24-h error (star) for the dependent sample along with the mean forecast errors (km) for the unmodified CLIPER forecasts (solid line) and the modified 36-, 48-, 60- and 72-h CLIPER forecasts (dotted line).

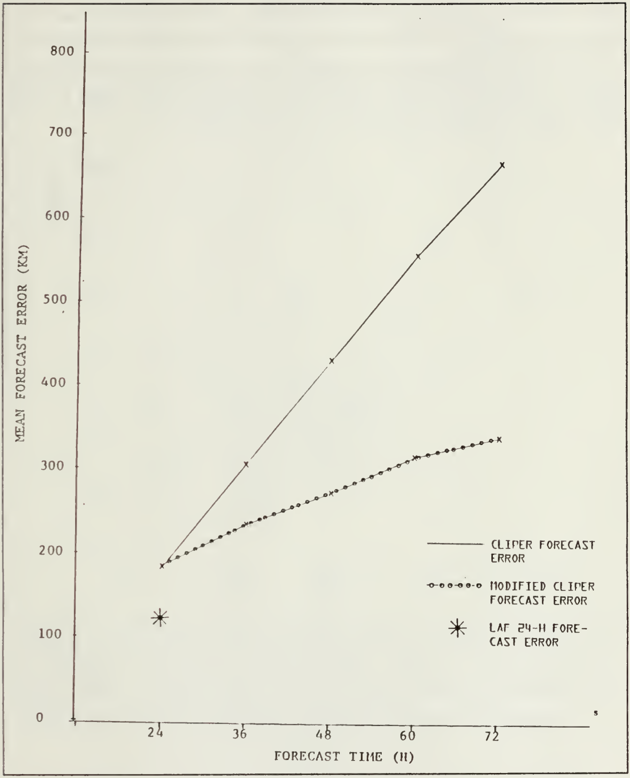

Figure 9. LAF 24-h error as in Fig. 8, except for the independent sample.

Another indication of the improvement from the LAF technique is shown in Figure 10, which is a scatter diagram of the individual 24-h forecast errors for CLIPER and the 'Modified' LAF for the independent sample. All the CLIPER forecast errors above and to the left of the diagonal line are improved by the application of the 'Modified' LAF. The CLIPER forecasts errors below and to the right of the diagonal line are degraded. Although some small degradations are noted, the majority of the CLIPER forecast errors decreased after the application of the 'Modified' LAF.

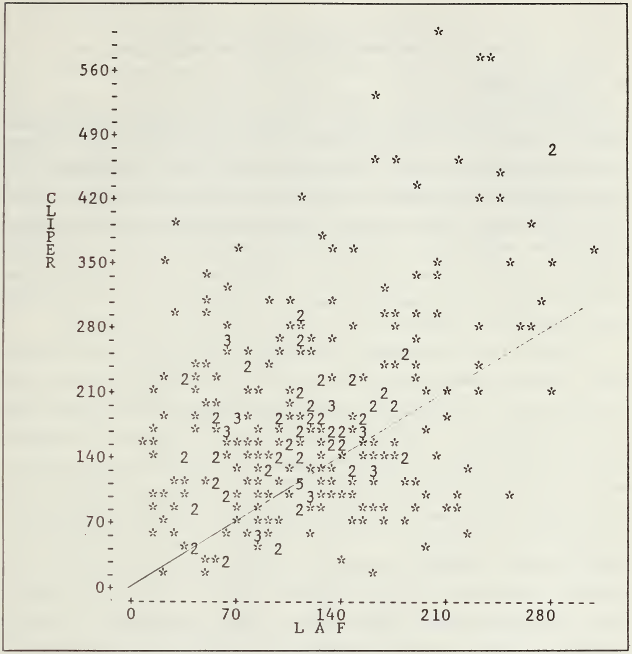

Figure 10. Scatter diagram of the individual 24-h forecast errors for CLIPER versus the 'Modified' LAF for the independent sample. When two or more points have similar values, the actual count is given. The line indicates equal errors, and CLIPER forecast errors above the line are improved by the LAF technique.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The lagged-averaged forecast (LAF) technique applied to tropical cyclone track prediction involves a series of recent forecasts that were started from initial conditions at various times lagging the start of the forecast period. Consider a 24-h forecast from time t and all the available forecasts from the past 48 hours that are also valid at time t + 24 h. During the past 48 h, eight other forecasts were generated that had a track position that also verified at the t + 24 h. The lagged-averaged forecast for t + 24 h is the combination of the nine forecasts. The weights applied to each of the nine forecasts are generated through statistical regression methods. The first test of the LAF technique with CLIPER forecasts resulted in an 8 % reduction in mean 24-h forecast error.

To improve the LAF preformance, the CLIPER forecasts first are modified statistically to reduce the mean errors of the 36-, 48-, 60- and 72-h CLIPER forecasts valid at the initial time. The modified LAF combines these modified CLIPER forecasts along with the unmodified 24-h CLIPER forecasts in terms of a latitude and a longitude equation. These modified LAF equations applied to the dependent data set produce a reduction of the mean 24-h forecast error from 223 km to 146 km, or a reduction of 35 %. In addition, a reduction in the standard deviation from 152 km to 103 km indicates an improvement in consistency of the LAF forecasts versus the unmodified 24-h CLIPER forecasts. Although encouraging, these reductions are expected since the regression equations are derived using the dependent sample. The true test is the application to the independent sample, which results in a reduction from 189 km to 124 km in the mean 24-h forecast error and a reduction from 118 km to 69 km in the standard deviation. This is a significant improvement because the JTWC mean 24-h forecast error for the last 4 years is approximately 213 km. The lower mean forecast error and standard deviation in the independent sample from 1987 may be explained partly by the relatively easy storms, since the CLIPER performance was the best in a 10-year sample (R. Sheets, personal communication). Some of this improvement may be attributed to the six Supertyphoons during that year since CLIPER tends to perform well on Supertyphoons. However, the improvement is so large with the independent sample that the Modified LAF technique is concluded to have some ability to reduce forecast error.

B. RECOMMENDATIONS

The Modified LAF technique in this study used CLIPER forecasts, which are a relatively no-skill type of forecast. These CLIPER forecasts used warning positions instead of the CARQ positions used operationally at JTWC. Some improvement might be expected from use of the operational CLIPER forecasts. However, this Modified LAF technique should be applied to the forecasts of a dynamical model such as the One-way influence Tropical Cyclone Model (OTCM) to further improve the accuracy and consistency of the dynamical forecasts.. If longer track forecasts were available, the LAF technique could also be applied to 48-h and 72-h track forecasts that are even more important for military evacuations and other preparedness actions in the western North Pacific area.

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